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# NEW PERSPECTIVES ON EXPERIMENTAL ARCHAEOLOGY: SURFACE TREATMENTS AND THERMAL RESPONSE OF THE CLAY COOKING POT

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*This paper examines pottery technology and change through the eyes of the experimental archaeologist. A new vision is presented of experimental archaeology and the role its findings can play in archaeological explanation. It is argued that the most useful results of experimental archaeology are best obtained with long-term research programs. This perspective is illustrated by a case study of the relations between surface treatments (interior and exterior) and thermal performance in cooking pots. The experiments indicate that surface treatments like texturing, organic coatings, and smudging have marked impacts on thermal shock cracking and on thermal spalling in simulated cooking. It is emphasized that the findings of experimental archaeology, expressed as correlates, can be employed in explanations of prehistoric technological change, but only when embedded in more inclusive correlate theories and coupled with the requisite contextual information.*

*Este artículo examina la tecnología cerámica y su cambio a través de los ojos del arqueólogo experimental. Se presenta una nueva visión de la arqueología experimental y el rol que sus hallazgos pueden tener en la explicación arqueológica. Se arguye que los resultados más útiles de la arqueología experimental se obtienen con programas de investigación a largo plazo. Un estudio de caso sobre la relación entre tratamientos de superficie (interior y exterior) y funcionamiento termal en vasijas de cocina ilustra esta perspectiva. Los experimentos indican que tratamientos de superficie tales como texturas, engobes orgánicos y ahumados, tuvieron impacto en la aparición de fisuras por shock termal y descascarillado termal en la cocción simulada. Se enfatiza que los hallazgos de la arqueología experimental, expresados como correlaciones, pueden ser empleados en las explicaciones del cambio tecnológico prehistórico, pero sólo cuando están embebidos en teorías de correlación más inclusivas y disponen de la necesaria información contextual.*

Archaeologists curious about how specific artifacts were made and used often turn to experiments. If one can judge by the number of published experiments, this activity—though over a century old (for early examples see Coles [1979])—has become an important part of modern archaeology. Indeed, a great many archaeologists have done an experiment or employed experimental data. Because it is such a familiar part of archaeological practice, one could come to believe that conducting experiments is easy, an activity carried out during leisure time away from more challenging tasks. Although it is possible to collect important data with "weekend" experiments, we maintain that the knowledge that archaeologists now demand from experimentation requires the development of long-term programs.

This paper has three major, interrelated aims. The first is to articulate a vision of modern experimental archaeology based on the recognition that an experimental program involves creation of a technological tradition as well as new technologies. The second is to present results from recent experiments carried out in the Laboratory of Traditional Technology at the University of Arizona concerning the effects of surface treatments on the thermal response of clay cooking pots. Third,

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we seek to clarify the role that the findings of experimental archaeology can play in the explanation of technological variation and change.

## ARCHAEOLOGICAL EXPERIMENTS AND EXPERIMENTAL ARCHAEOLOGY

Experimental archaeology, along with ethnoarchaeology, comprises one of the four strategies of behavioral archaeology (Reid et al. 1975; Schiffer 1976:6). Experimental archaeology involves setting up an artificial system with which one can study a specific process through the control of relevant variables (Ascher 1961; Tringham 1978). Typically the experimental archaeologist fabricates "materials, behaviors, or both, in order to observe one or more processes involved in the production, use, discard, deterioration, or recovery of material culture" (Skibo 1992:18). Though useful, this traditional definition begs an important question: Is there a difference between what can be called "archaeological experiments" and "experimental archaeology?" We believe there is and that such a distinction is consequential.

The ordinary archaeological experiment begins with a prehistoric puzzle—a question about how a particular tool was manufactured or used. In order to help answer the question, the investigator makes an artifact and performs a series of simulated behaviors to test hypotheses about production or use. Such an experiment often yields pertinent information on whether the artifact could have been made or used in the hypothesized manner. However, coping adequately with the questions being asked about technology today, including issues about artifact design and technological change (e.g., Bleed 1986; Braun 1983; Bronitsky 1986; Gilman 1987; Goodyear 1989; Hayden 1981; Neff 1992; Nelson 1991; Reid 1990; Rice 1987; Schiffer 1992; Schiffer and Skibo 1987), ordinarily requires more than a weekend's worth of attention. In dealing with those complex issues, some archaeologists have found it fruitful to carry out, as part of long-term programs, what we call "experimental archaeology."

Archaeological experiments tend to be one-shot affairs, done in isolation and concluded before there has been an adequate opportunity to conduct the study rigorously. Such experiments often seem like pilot studies, perhaps reported prematurely (cf. Tringham 1978:171). In contrast, a program-based experimental archaeology entails the creation of new technology and the establishment of a technological tradition. In experimental archaeology, individual experiments do not exist in isolation, but draw expertise and technology from the program's tradition and, in turn, contribute to its elaboration. More importantly, the findings of one experiment are nested within families of related principles (correlates) that, together, furnish a foundation for explaining technological variation and change.

We define technology "as a corpus of artifacts, behaviors, and knowledge for creating and using products" (Schiffer and Skibo 1987:595). Because any experiment entails artifact manufacture and use, it necessarily requires technology. For example, Crabtree (1968) could only produce meso-american-style prismatic blades of obsidian after creating a chest crutch and perfecting the techniques for using it based on his experience and know-how. Similarly, Bronitsky and Hamer (1986) in their studies of ceramic strength and temper had to have a pendulum tester fabricated. Clearly, archaeological experiments often involve the creation of appropriate—and sometimes new—technology for making and using other artifacts as well as for recording observations.

The technology employed by the practitioners of an experimental archaeology is distinguished by being part of a technological tradition. A technological tradition involves the means to reproduce a technology and embodies the growth of knowledge that is acquired through long-term study. For example, Don Crabtree for many years conducted a summer field school in flintknapping, which helped to train an entire generation of lithic specialists in various techniques for chipping tools. Other investigators, like Lawrence Keeley, have over many years trained students in their laboratories. In these ways, technologies are passed from investigator to investigator and from one generation to the next. Moreover, the establishment of a technological tradition facilitates the accumulation of knowledge and technique that can be exploited for solving new problems.

If our own experience can be generalized, it would appear that the growth of knowledge and technique in a technological tradition results mainly from trial and error. For example, most of our

early experiments had to be repeated because we lacked certain key pieces of information that became apparent only after the initial results were assessed. In recent years we have learned to make effective use of limited trials to avoid premature commitment to a particular strategy. In the present case, these trials involve running through an entire experiment from start to finish with a small sample. This allows us to collect some preliminary data and to revise the experimental design. Sometimes several trials are needed to develop the techniques and know-how for performing a full-scale experiment. Clearly, the techniques and knowledge acquired by trial and error through individual experiments enrich the technological tradition.

In the Laboratory of Traditional Technology we have been conducting ceramic experimentation since 1984. A major goal, adopted in 1987, has been to achieve an understanding of the effects that surface treatments have on the performance characteristics of clay cooking pots. The following case study, based on recent experiments, illustrates in detail our claims that experimental archaeology, as a long-term program, entails the creation of technology and the establishment of a technological tradition.

## SURFACE TREATMENTS AND THERMAL RESPONSE
## OF THE CLAY COOKING POT

*General Considerations*

Thermal shock resistance is one among many ceramic *performance characteristics*, "the behavioral capabilities that an artifact must possess in order to fulfill its functions in a specific activity" (Schiffer and Skibo 1987:599). Though useful in theoretical contexts, this definition has practical limitations because the investigator may not be able to specify in advance which performance characteristics are demonstrably relevant in a given activity. It may be more fruitful to regard an artifact's performance characteristics as consisting of a large potential set, of which a subset can be considered *behaviorally relevant* in relation to a specific activity. For example, abrasion resistance is a performance characteristic in terms of which any ceramic object can be described (Schiffer and Skibo 1989), but only in some pottery use activities does it become behaviorally relevant. For present purposes we define performance characteristics simply as the behavioral capabilities of an artifact, whereas a behaviorally relevant performance characteristic is one clearly tied to a specific activity. Because thermal shock resistance is the ability of a vessel to withstand rapid heating and cooling, we believe it to be behaviorally relevant in the activity of cooking over an open fire (also see Braun 1983).

As is well known, ceramic materials can suffer damage, i.e., fracture (breakage or cracking), spalling, and loss of strength, in response to stresses created by changes in temperature and temperature gradients (e.g., Kingery 1955; Rye 1981; Salmang 1961; West 1992). Stresses induced by thermal shock—a sudden temperature change (Kingery 1955:3)—are caused by differential thermal expansion. When a cooking pot is placed on a fire, the temperature of the exterior surface rises more rapidly than the mean temperature through the thickness of the vessel wall, leading to surface expansion and the ensuing compressive stresses at the exterior surface. In contrast, the interior surface of the vessel is at a temperature lower than the mean temperature through the wall, and is thus subjected to tensile stresses. Upon cooling, the exterior surface experiences a tensile stress while the interior surface is in compression. (For a more complete discussion of these phenomena, see the Appendix.) These alternating stresses can induce cracks in the vessel, with strength loss dependent on factors such as the coefficient of thermal expansion, thermal conductivity, temperature differential, heating/cooling rate, and the number of heatings (Hasselman 1970; Kingery 1955). When especially severe, thermal stresses lead to the formation of visible cracks, which can cause vessel failure.

Because ceramics are much stronger in compression than in tension (Searle and Grimshaw 1959), cracks should begin on surfaces in tension. As shown in the Appendix, the largest tensile stress a vessel experiences is on the interior surface during heating. Thus, we can expect that tensile stresses on the interior surface should contribute disproportionately to thermal shock damage of cooking

vessels. In the tests carried out during this experiment, all cracks began on interior surfaces and often were visible only on interior surfaces.

As is well known, a potter can manipulate several technical choices in order to improve a vessel's thermal shock resistance (Amberg and Hartsook 1946; Bronitsky 1986; Kingery 1955; Salmang 1961; cf. Searle and Grimshaw 1959; West 1992), including (1) clay composition; (2) temper composition, quantity, size, and shape; (3) wall thickness; (4) vessel size and shape; and (5) firing temperature. We propose that surface treatments, both interior and exterior, can also affect the thermal shock resistance of traditional, low-fired, clay cooking pots. These effects, we believe, should come about because surface treatments, depending on their permeability, regulate the flow of fluid from the interior to the exterior of the vessel during cooking. In addition, surface treatments should influence the way that heat is transferred from the fire to the interior surface. The outward flow of fluid (water and sometimes steam in our experiments) and the inward flow of heat together should help to determine the nature and magnitude of a vessel's response to thermal shock. Our tests confirmed this general model while adding significant details.

The following discussion is organized in terms of the technologies developed for each of the experiment's constituent activities. We consider our own behavior and the decisions it embodies as creating and manipulating appropriate technology in the context of a technological tradition.

*Clay Selection*

Wanting to understand the relation between surface treatments and thermal shock, we sought a clay with poor thermal shock resistance. Westwood Ceramics (City of Industry, California), a source for many of our clays, recommended EM210, a fine-textured earthenware clay that can be bought premoistened in 25-lb plastic bags. (We use commercial clays in many experiments because of their uniform properties; see Vaz Pinto et al. [1987] for compositional and petrographic data on EM210.) Coincidentally, EM210 had been used often in our previous experiments because it fires at low temperatures and contains very little nonplastic material. We prefer premoistened clay because it is more convenient for preparing pastes, and it reduces the amount of silica dust in the laboratory — an important safety consideration. Depending on time elapsed between the date the clay was mixed by Westwood and its use in experiments, however, there is variation in moisture content. To reduce the effects of such variation, all batches of paste were mixed by one individual (JMS), who added enough water to achieve a consistent level of workability.

*Temper Selection*

Choosing the right amount and kind of temper required pilot tests because temper influences both thermal shock resistance and the formation of drying cracks (Searle and Grimshaw 1959). Enough temper had to be added to reduce drying cracks while maintaining generally poor thermal shock resistance. Achieving the proper balance necessitated about a half-dozen trials, which included making vessels and subjecting them to thermal shock (see below). The final paste consists of 800 ml of temper per 25-lb package of EM210; we used equal portions, by volume, of 16-, 30-, and 60-mesh Ottawa quartz sand.

*Making the Vessels*

Some of our earlier experiments employed miniature vessels, which were suitable for certain tests of heating effectiveness and evaporative cooling effectiveness (e.g., Schiffer 1988, 1990a, 1990b; Skibo et al. 1989). It is well known, however, that susceptibility to thermal shock increases with specimen size (Kingery 1955:10; Searle and Grimshaw 1959:868). Indeed, one frustration in our prior thermal shock experiments (mostly unpublished and unpublishable) had been the lack of obvious cracks on miniature vessels and briquettes. Even briquettes 8 cm on a side failed to display a visible response to thermal shock (Skibo et al. 1989). Thus, we were anxious to pursue the present experiment with full-size vessels.

New forming technology was needed for making dozens of identical vessels. After considering a

variety of mass-production techniques, including throwing on a wheel and slip casting, we settled on a hybrid of molding and hand modeling. Vessels were coiled inside a two-piece plaster mold. In contrast to many mass-production techniques, this hybrid permits the building of tempered, coiled vessels. Initially, coiling was thought to be important because we had hoped to make pots with "corrugated" exterior surfaces like those found prehistorically in the American Southwest (see Gifford and Smith 1978). (Corrugated vessels were not, in the end, produced, because we were unable to master the technique.) To ensure standardized coils, and thus promote uniformity in vessel thickness, the paste was extruded to create coils 12.6 mm in diameter.

The template for the plaster mold was a Kalinga vegetable/meat cooking vessel (see Longacre 1981; Skibo 1992) that produced fired pots 19.5 cm in diameter with a volume of approximately 2 liters. Though we had some previous experience in mold making, creating a mold from this vessel proved to be a challenge even to the professional mold maker we hired (Garote Studio, Tucson).

All vessels were made by one person (TCB). Even so, there is some variation among pots, mostly in thickness, that arises in the process of joining and smoothing coils. Such minor variation can potentially influence the test results.

Producing the vessel begins by forming, with the hands, a disk 8 cm in diameter. One attempts, by feel, to make the thickness of the disk equal to that of the smoothed coils. Use of the disk reduces basal drying cracks, but may also introduce additional variation in base thickness. Drying cracks are also diminished by moistening the interior of the mold with a sponge before forming begins. Coiling starts when the disk is placed at the bottom of the mold. Adjacent coils are overlapped slightly and joined; with the addition of each coil the interior is smoothed with fingers. Coiling terminates at the neck; the rim is too difficult to form and unimportant for the experiment. The interior is smoothed further with a modern potter's rubber scraper.

After the interior has been smoothed, one-half of the two-piece mold is removed without delay. Though the still-plastic vessel is difficult to manipulate, surface treatments must commence at this stage because the paste dries rapidly in the mold. The exposed half of the vessel's exterior (except on deep-textured pots) is smoothed with the rubber scraper. The mold is replaced on the completed side and the other half of the vessel is smoothed in the same manner. Refining the forming techniques involved dozens of attempts; JMS performed the initial trials and then taught successful techniques to TCB, who made many practice pots.

On the basis of our experience with this clay, especially when little temper is used, we expected problems with drying cracks and were not disappointed. Because this experiment required a limited amount of temper, another solution to the cracking problem had to be found. First, as noted above, we employed the basal disk and premoistened the mold, but the problems persisted. After trying rapid drying at 90°C, and drying in open air, we found that covering the vessels with plastic for as much as several weeks made a difference but did not eliminate all drying cracks. The majority of the vessels still had small cracks visible only on the interior surface—an additional source of variability, which, happily, did not affect the results.

*Surface Treatments*

Smooth surfaces are the least modified, involving only smoothing with a rubber scraper. As noted above, the scraper is used to join the coils and creates an even surface without removing any paste.

Textures, deep and shallow, are also applied while the pots are still plastic. Shallow texturing is created by the gentle rocking and rolling action of a stove bolt on the smoothed exterior surface. The threads of the bolt create a cross-hatched texture less than .5 mm in depth. The major problem in applying a deep texture is to maintain the vessel's shape; much trial and error with many devices for grooving was required before a satisfactory solution was found. The deep texture is produced by an ordinary fork, drawn forcefully from the base to the rim, which leaves parallel grooves approximately 1.0–1.5 mm deep. To help maintain vessel shape, exterior surfaces of the deep-textured vessels are left unsmoothed (overworked clay becomes fatigued and unworkable).

Stuccoing, a technique reported, for example, among Yuman groups in the Lower Colorado region of the American Southwest (see Waters 1982), also creates a deep texture. Stucco is basically a

heavily tempered slip applied to a bone-dry vessel. To create the stucco, we start with the same paste used to make the vessels (see recipe above). Approximately 1,000 ml of paste is mixed with 900 ml of coarse temper and 400 ml of water. The result is a grainy slip having a consistency like wet concrete. Stucco is smeared on rapidly with a wiping motion of the hand. When dry, the texture resembles a stuccoed wall with drying cracks. Unlike other surface treatments, stucco increases wall thickness, which should influence thermal performance.

Common throughout the world are organic coatings that reduce vessel permeability. We experimented with three organic coatings: tree resin, commercial polyurethane varnish, and PAM (the nonstick cooking spray).

PAM, a mixture of corn oil, grain alcohol, and lecithin, was selected to represent interior coatings that reduce permeability by being absorbed into the vessel wall. The application of PAM may also simulate the clogging of pores that might take place during normal cooking. PAM in particular was chosen because it was already in the kitchen where the experiment was carried out. Before each heating cycle, PAM is sprayed on the interior and evened out with a paper towel to coat the lower one-half of the vessel (above the water line). Within 10 minutes, the PAM coating is absorbed into the vessel wall.

The pine resin (from the tree, *Agathis philippinesis*, referred to as *lita-o* by the Kalinga) is collected and prepared by the Kalinga as a vessel coating (see Longacre 1981:60). Samples of the resin were obtained as part of the Kalinga Ethnoarchaeological Project (see Longacre and Skibo 1994; Longacre et al. 1991). In Kalinga, a stick of hardened resin is melted onto the surface of a pot as it is removed, red hot, from firing. This process was replicated in the present experiment. It was found after several trials that the resin melts, without burning, onto the surface when the vessel is removed from the kiln at 400°C. When this temperature is reached, in the cool-down stage of firing, the lid of the kiln is opened and the pot removed with high-temperature gloves. The surface is immediately coated by sliding the resin bar along the vessel's interior; the liquified resin hardens as the vessel cools.

The final coating is a polyurethane varnish (Defthane, Clear Satin #2, by the Deft Company) used in previous experiments (Schiffer 1988, 1990a). It was chosen to produce a distinct surface layer that is completely impermeable (pine resin and PAM do not create fully impermeable surfaces). The varnish is wiped on the fired pot with a rag; to attain the desired thickness, a second coat is applied while the surface is still tacky.

Smudging is a treatment, common in the American Southwest, that deposits pyrolized organic matter, in a reducing atmosphere, on a vessel's surface and into its pores. Techniques for smudging had been worked out in previous experiments with miniature vessels (Schiffer 1988:28–29), but had to be scaled up for larger pots. Smudging takes place in an aluminum kettle having a several-centimeter layer of fine sand at the bottom. On the sand is put a fist-size mound of dry pine needles. The vessel is removed from the kiln at 500°C during cool down and placed upside down over—but not touching—the pine needles. The hot pot fits snugly on the sand and the vessel's heat ignites the pine needles, thereby producing a reducing atmosphere and abundant smoke. Because some smoke escapes from the sand seal, a gray smudge also forms on vessel exteriors.

The last treatment is polishing, which produces a dense surface layer (Rice 1987:138) of reduced permeability. Small areas of the bone-dry vessel are rewet with a sponge and then rubbed vigorously with a smooth pebble; the resultant surfaces are smooth to the touch but have visible striations. This style of polishing was perfected in earlier experiments (Schiffer 1988, 1990a).

These interior and exterior surface treatments differ markedly in permeability. In previous experiments we have measured surface and vessel permeability (Schiffer 1988, 1990a; Skibo et al. 1989); we can draw on those measurements and our general experience to provide a coarse scaling of the permeability of the surface treatments employed in the present study. Insofar as interiors are concerned, polyurethane varnish creates an impermeable surface, whereas surfaces treated with Kalinga resin and PAM have only very slight permeability. Smudged and polished surfaces are much more permeable, and smooth surfaces are the most permeable of all. Exterior surfaces, from least to most permeable, are smudged, polished, smoothed, shallow texture, deep texture, and stucco. (Obviously we erred in not directly measuring the surface permeability of vessels used in the present experiment.)

*Firing*

Immediately before firing, vessels are dried in a Despatch Digitronic oven at 90°C for a minimum of 24 hours. Firing is done in a Paragon electric kiln fitted with an Orton Coneputer. To control for temperature variation from top to bottom of the kiln, vessels are fired one at a time in the same place—a technique employed before in our lab (e.g., Fournier 1989). Pots are fired to 700°C and left at that temperature for 30 minutes. At the Coneputer's "fast" setting, it requires 67 minutes to reach 700°C.

Our earlier experiments with EM210 established that firings between 700° and 950°C create a hard-fired paste (e.g., Vaz Pinto et al. 1987). As is well known, firing temperature has a profound influence on thermal shock resistance, hence numerous trials were necessary to select the most appropriate temperature—700°C; at higher temperatures pots have little resistance to thermal shock. Indeed, cracking is so severe above 800°C that we immediately appreciated the possibility of using total crack length as an index to a vessel's thermal shock resistance.

## BEHAVIORALLY RELEVANT TESTING PROCEDURE

The primary objective of the test is to subject the vessels to a heating regime similar to cooking over an open fire. We did not simply use an open fire, however, because of the need to maintain constant temperature conditions from vessel to vessel. Instead, following laboratory precedent (Young and Stone 1990), pots were tested over the open flame of a gas range. In pilot studies, we discovered that placing the vessel directly on the grate is too severe a test because the temperature reaches 900°C, beyond the range of wood-fueled open fires. To produce a lower but uniform temperature, the vessel is elevated. A cylindrical metal framework, turned on its side, raises the pot to a point where the maximum temperature immediately adjacent to the vessel is 550°C. An obvious implication of this pilot test is that a cook (as opposed to a potter) can ameliorate thermal shock by reducing the effective heat of the fire (e.g., raising the pot with firedogs or using a cooler-burning fuel).

All tests were carried out by MBS on the right-rear burner of a not-very-modern Gaffers & Sattler gas range. Possible fluctuations in gas pressure seem not to have affected this experiment.

Prior to each heating cycle, vessels with no interior coating are filled with tap water and allowed to stand (15–30 minutes) until the wall is saturated. In previous studies it was found that presaturation is the most behaviorally relevant method for testing permeable pots (Schiffer 1990a:337).

Once the saturated but empty vessel is in place for testing, 473 ml (1 pint) of tap water is poured in, and the flame immediately turned on. After five minutes of heating (long enough to create a steady-state thermal gradient), the flame is turned off, and within a minute or two the pot is removed from the test stand and the water poured out. Spalls are counted and measured while the pot cools down. After reaching room temperature, the vessel is resaturated, and the next heating cycle begins.

Each vessel type (with one exception discussed below) was subjected to 10 heating cycles. This relatively low number was chosen for two reasons. First, the test is designed to mimic short-term processes the effects of which—i.e., thermal cracks and spalls—might have been observed in no more than several days by someone cooking with the vessels. Second, if cracking occurs, it always begins (and is most severe) during the first cycle, whereas spalling may require 5–10 cycles. Thus, to be sure of capturing both cracking and spalling, we selected the figure of 10 cycles. As shown below, however, the 10-cycle test was too short to produce detectable strength loss in areas of the vessels between the visible cracks. Total length of cracks was measured with a cloth tape after the last cycle.

Thermal response is assessed in two ways. First, manifest changes in the vessels (spalling and cracking), visible to the unaided eye, are employed. Thermal shock resistance is indicated by total length of all cracks, and extent of spalling is indicated by total number of spalls in excess of 2 mm in maximum dimension. Spalls are counted after each cycle because large spalls sometimes obliterate small, early spalls.

Second, to assess the more subtle, long-term effects of thermal shock, a degradation in strength

caused by microcracking, samples from each vessel were removed and strength tested by MAN.

In the course of previous experiments, we have had to develop specific technologies for measuring ceramic strength. Following the suggestion of Bronitsky (1986), who was a visiting scholar in the Laboratory of Traditional Technology, Mabry et al. (1988) designed and evaluated a falling-weight impact apparatus. This tester yields reliable and accurate results, and we have put it to good use (e.g., Skibo et al. 1989), but it requires large, flat specimens. Similarly, we have designed a four-point flexure fixture, which Fournier (1989, 1990) employed in a study of surface treatments and tensile strength. Unfortunately, this test also requires flat, precisely machined briquettes. To overcome the limitations on specimen geometry of the previous testing technologies, Neupert (1993) recently developed a ball-on-three-ball fixture capable of measuring the strength (modulus of rupture) of archaeological, ethnoarchaeological, and experimental ceramics. This test was used in Stage 1 to seek evidence of strength degradation.

The ball-on-three-ball test assesses strength in biaxial flexure. A curved specimen is supported from below by three steel balls forming an equilateral triangle. A fourth steel ball applies the load from above on the center of the specimen at a constant rate of .25 mm/sec. The support balls were placed .5 inch from the center load point. The ball-on-three-ball fixture fits into a standard compression cage, which in our laboratory is driven by a Dillon universal test stand. Not only does this format allow testing of curved specimens, but the results are unaffected by the edge condition of the specimen (Ritter et al. 1980). In addition, results are standardized to allow for variation in specimen thickness. Six to eight samples were obtained from each vessel by coring out discs, 4 cm in diameter, from areas lacking visible cracks at about one-third of vessel height.

## RESULTS

### Stage 1

In Stage 1, we tested four vessel types: (1) smoothed interior, smoothed exterior; (2) smoothed interior, shallow-textured exterior; (3) PAM-coated interior, smoothed exterior; and (4) PAM-coated interior, shallow-textured exterior. These surface treatments were chosen for the first tests because they furnished a wide range of vessel permeabilities, and they were relatively easy to apply.

Three vessels of each type were tested in Stage 1, and the results yield clear-cut patterns. All vessels with PAM-coated interiors, regardless of exterior treatment, developed basal cracks, whereas smooth-interior vessels did not (Table 1). Clearly, the more permeable surface treatments, which allow walls to become quickly saturated, apparently promote excellent thermal shock resistance (but also result in very poor heating effectiveness—see Schiffer [1990a]). A mechanism to explain these effects is furnished in the Appendix.

Except for the thermal cracks, obvious upon close inspection during heating, the ceramic material does not exhibit any reduction in strength. Although *vessel* strength is severely compromised by these cracks, the uncracked areas (from which the cores were removed) retain their original strength— at least over the short term. This suggests that thermal stresses are relieved at first by macrocracking; after many more cycles, however, we would expect a gradual strength reduction from microcracks (assuming that the weakened vessel has not already broken).

Although our experimental design, based on just 10 cycles, did not permit us to detect strength loss from extended thermal cycling, the testing did divulge one surprising finding. To wit, the PAM coating increases strength (Figure 1). Even after thermal cycling, PAM-treated vessels are stronger than the controls. Because the constituents of PAM (corn oil, lecithin) are not unlike some organic surface treatments applied to pots ethnographically, the latter may also bring about strength increases. Such gains in strength likely result from the reduction of pore space, since strength and porosity are closely related (Kingery 1960), but the processes remain to be investigated more fully. In any event, researchers should be alert to the possibility that organic coatings absorbed by a vessel's wall, which may not survive in the depositional environment, could have conferred greater strength on vessels in systemic context.

Spalling, described in earlier studies (Schiffer 1990a:376, 378–379; Skibo 1992:134–141), also

Table 1.   Thermal Shock Summary Data, Aggregated by Vessel Type, Stage 1.

| Vessel Number | Interior Treatment | Exterior Treatment | Total Length of Drying Cracks[a,b] (cm) | Total Length of Cracks After Testing (cm) | Total Length of Thermal Cracks (cm) |
|---|---|---|---|---|---|
| 2 | smooth | smooth | not recorded | not recorded | none |
| 6 | smooth | smooth | 1.0 | 1.0 | .0 |
| 11 | smooth | smooth | 4.0 | 4.0 | .0 |
| 5 | smooth | shallow texture | 10.0 | 10.0 | .0 |
| 9 | smooth | shallow texture | 8.0 | 8.0 | .0 |
| 12 | smooth | shallow texture | 4.5 | 4.5 | .0 |
| 1 | PAM | smooth | ca. 4.0 | 18.0 | ca. 14.0 |
| 4 | PAM | smooth | ca. 5.0–10.0 | 26.5 | ca. 16.5–21.5 |
| 7 | PAM | smooth | ca. 10.0 | 14.0 | ca. 4.0 |
| 3 | PAM | shallow texture | ca. 7.0 | 20.5 | ca. 13.5 |
| 8 | PAM | shallow texture | .5 | 11.0 | 10.5 |
| 10 | PAM | shallow texture | 2.5 | 20.0 | 17.5 |

[a] Where crack lengths are given as "ca.," the figures were estimated from notes on original pot condition. All measurements of crack length are subject to errors of .5–2.0 cm.
[b] The nonparametric Kruskal-Wallis test determined that there were no statistically significant differences in the lengths of drying cracks among the vessel types (K-W = 5.37; $p$ = .15; $df$ = 3).

was evident in Stage 1 tests (Table 2). Spalls form on the exterior base, in areas that seem to get hottest, and appear to be caused by steam "blowing" off vulnerable places, usually in the shape of a circle or ellipse, up to about 3 mm in maximum depth and several cm in maximum diameter. Spalls often originate at large temper particles, voids, or other irregularities in the paste.

The results (Table 2) confirm previous findings that uncoated vessels are susceptible to spalling (Schiffer 1990a), for only in permeable pots do the walls become saturated with water. None of the six PAM-coated vessels was damaged by spalling, whereas all six pots with smoothed interiors accumulated spalls (mean of 29; range of 6–57). Also in accord with the earlier study, exterior



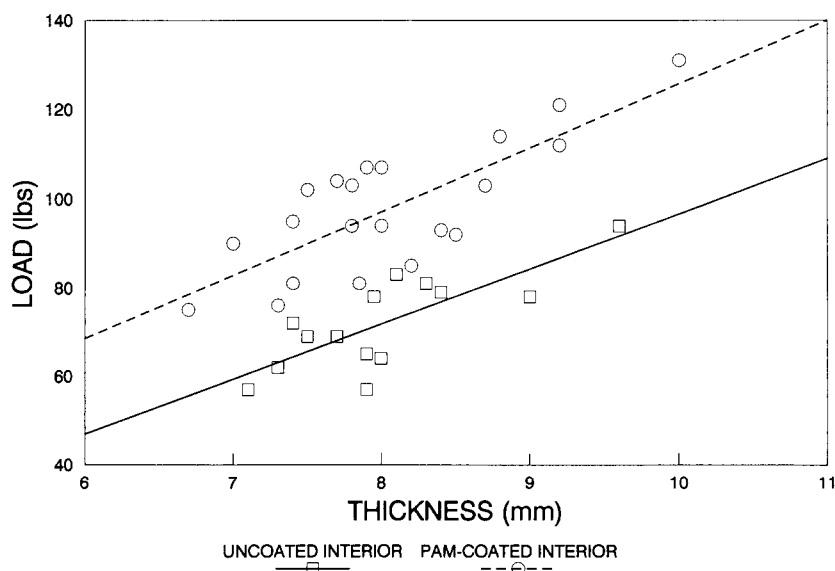UNCOATED INTERIOR    PAM-COATED INTERIOR

Figure 1.   The effect of PAM coating on strength as measured by the ball-on-three-ball test. Note that the PAM-coated vessels are significantly stronger than the control vessels. Each data point is a core.

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Table 2.   Thermal-Spalling Data, Aggregated by Vessel Type,
Stage 1.

| Vessel Number | Interior Treatment | Exterior Treatment | Spalls at 5 Cycles (N) | Spalls at 10 Cycles (N) | Largest Spall[a] (cm) |
|---|---|---|---|---|---|
| 2 | smooth | smooth | 29 | 57 | 4.0 |
| 6 | smooth | smooth | 22 | 46 | 4.0 |
| 11 | smooth | smooth | 8 | 30 | 2.0 |
| 5 | smooth | shallow texture | 6 | 16 | 2.0 |
| 9 | smooth | shallow texture | 3 | 18 | 1.5 |
| 12 | smooth | shallow texture | 0 | 6 | 2.0 |
| 1 | PAM | smooth | 0 | 0 | — |
| 4 | PAM | smooth | 0 | 0 | — |
| 7 | PAM | smooth | 0 | 0 | — |
| 3 | PAM | shallow texture | 0 | 0 | — |
| 8 | PAM | shallow texture | 0 | 0 | — |
| 10 | PAM | shallow texture | 0 | 0 | — |

[a] Estimated for longest dimension, ± .3 cm.

treatments influence spalling. Among the uncoated vessels, those with smoothed exteriors spall more than pots with shallow textures (means of 44 and 13 spalls, respectively); and spalls can be larger on vessels with smoothed exteriors.

*Stage 2*

To gain insight into the processes responsible for these patterns and to examine the effects of a wider range of surface treatments, a second stage of testing was initiated. In Stage 1 each vessel type was represented by a sample of three. However, the major effects could have been revealed with fewer pots. This is important because our aim is to discover effects that are *behaviorally significant*— differences in performance that would be apparent to the vessel user because they can be detected consistently without instruments or a large sample size (cf. Schiffer and Skibo 1987:602). Sample sizes from one to three were employed in Stage 2.

The new vessels for Stage 2 were made and tested a few at a time. The particular vessels manufactured and tested were chosen for a variety of situational reasons, including the cumulative results of prior tests, which pots were available, and a series of "what-if-we-tried-this" questions. In addition, we desired to test diverse combinations of interior and exterior treatments. The latter orientation was in some respects a stumbling block because it led to testing of vessels that provided no new information and diverted effort that could have been used to increase the sample size of the most relevant vessel types. This shortcoming calls attention to the dark side of a technological tradition. Several previous experiments have employed a design in which all combinations of surface treatments were tested (e.g., Schiffer 1988, 1990a). Mindlessly transferring this design to the present project was a mistake that for a time fostered a "fill-in-the-cells" orientation. This was not a fatal design error, but it underscores the need to be more critical of tried-and-true methods that can too easily become rote practice. The actual design of Stage 2 can best be described as messy, involving deliberate elements as well as serendipity. Using this design to organize the presentation would be tedious and confusing; thus, like most experimenters, we have imposed a post hoc order to facilitate communication of findings. The following discussion is structured by a series of questions arising from the Stage 1 results.

In Stage 1 it was found that interior coatings affect thermal cracking. Because a PAM coating does not mimic the range of surface coatings that people actually use on clay cooking pots, our first question is: How do other interior coatings affect thermal cracking? To answer the question we applied two new coatings, Kalinga resin and polyurethane varnish, as well as smudging.

Table 3.  Thermal Shock Summary Data, Stage 2.

| Vessel Number | Interior Treatment | Exterior Treatment | Total Length of Drying Cracks[a] (cm) | Total Length of Cracks After Test (cm) | Total Length of Thermal Cracks (cm) | Comments |
|---|---|---|---|---|---|---|
| 15 | polyurethane varnish | smooth | 6.5 | 7.5 | 1.0 | tested for 1 cycle only |
| 16 | polyurethane varnish | smooth | 2.0 | 2.0 | .0 | tested for 1 cycle only |
| 17 | polyurethane varnish | smooth | 3.0 | 3.0 | .0 | tested for 1 cycle only |
| 18 | PAM | stucco | 6.5 | 10.0 | 3.5 | practice pot for stucco; test ended after 5 cycles |
| 19 | smudge | smooth | 1.0 | 2.0 | 1.0 | |
| 23 | Kalinga resin | smooth | 6.5 | 9.0 | 2.5 | |
| 24 | Kalinga resin | smooth | 6.5 | 8.0 | 1.5 | |
| 28 | PAM | smooth | .0 | 20.0 | 20.0 | |
| 29 | PAM | stucco | 1.0 | 2.0 | 1.0 | |
| 30 | smudge | shallow texture | 1.5 | — | — | accidentally sprayed with PAM; test ended after 1 cycle |
| 33 | PAM | stucco | 1.0 | 1.5 | .5 | |
| 34 | PAM | deep texture | .0 | .0 | .0 | |
| 35 | PAM | polish | .0 | 12.0 | 12.0 | |

[a] Estimates of crack length are subject to errors of .5–2.0 cm.

Kalinga resin and smudging were intended to replicate surface treatments commonly reported in archaeological and ethnographic cases. Kalinga resin creates a surface of very low permeability and so we expected it to promote extensive cracking (as had the PAM coating). Two vessels (23 and 24) were tested with a smooth exterior and Kalinga resin-coated interior. Cracking was very limited (see Table 3). Apparently, coatings alter more than permeability. In this case, the coating also improved the tensile strength of the vessel's interior surface. This was underscored by results with three vessels (15, 16, 17) that had a varnish-coated interior and a smooth exterior. Although the varnished vessels were impermeable, they did not crack during the first heating cycle. Regrettably, heating of the polyurethane pots produced noxious fumes, and so the test was terminated after just one cycle. Nonetheless, we believe the results are definitive because in the present study all vessels susceptible to thermal shock cracked during the first heating.

In previous experiments with small briquettes, a resinous surface coating had little or no influence on tensile strength (Fournier 1989:75–77, 1990; Skibo et al. 1989:126–127). The present experiments show that, in certain situations, such a coating can have a marked and behaviorally significant effect. Clearly, behaviorally significant effects are most likely to show up in behaviorally relevant tests, especially on full-size vessels.

The effects of interior smudging produced no surprises, but the sample size is small. Testing of vessel 19, which has a smudged interior and smooth exterior, yielded only slight cracking (Table 3). Because smudging produces a permeable surface, such vessels have good thermal shock resistance.

In Stage 1, shallow-textured exteriors had no effect on thermal cracking; the PAM-coated pots behaved as if they had smooth exteriors. Because the shallow texture was such a minimal modification, however, it cannot represent the more extreme textures seen on some archaeological and ethnographic specimens. That is why in Stage 2 we tested vessels with deep texture and stucco exteriors (Table 3). Upon testing, a PAM-coated vessel (34) with a deeply textured exterior exhibited no cracking; and PAM-coated vessels with stucco exteriors (29, 33) had, at most, very short cracks. Evidently, as some have surmised (e.g., Heidke and Elson 1988), a deep texture can enhance thermal shock resistance.

Precisely how deep textures have this effect remains unclear. Two hypothesized mechanisms merit

Table 4. Thermal-Spalling Summary Data, Stage 2.

| Vessel Number | Interior Treatment | Exterior Treatment | Spalls at 5 Cycles (N) | Spalls at 10 Cycles (N) | Largest Spall[a] (cm) |
|---|---|---|---|---|---|
| 13[b] | smooth | smooth | 0 | 1 | 1.5 |
| 14[c] | smooth | smooth | 21 | 56 | 3.0 |
| 20 | smudged | smooth | 1 | 9 | 1.5 |
| 21 | smudged | shallow texture | 3 | 18 | 2.0 |
| 22 | polish | shallow texture | 0 | 0 | — |
| 25 | polish | shallow texture | 0 | 6 | 2.0 |
| 26 | smooth | deep texture | 0 | 0 | — |
| 27 | smooth | stucco | 0 | 0 | — |
| 31 | polish | deep texture | 0 | 0 | — |
| 32 | polish | polish | 32 | 35 | 2.0 |
| 36 | polish | smooth | 26 | 38 | 3.0 |
| 37 | polish | smooth | 21 | 35 | 3.0 |
| 38 | smudged | smudged | 1 | 8 | 2.5 |

[a] Estimated for longest dimension, ± .3 cm.
[b] Fired at 800°C.
[c] Fired at 600°C.

elaboration and further study. First, by creating fine-grained but marked variation in vessel thickness, a deep texture may complicate the profile of the thermal gradient through the wall, creating a different distribution of stresses than in vessels with smooth exteriors. Second, a deep texture may alter the mix of mechanisms (convection, conduction, radiation) that transfer heat from the fire to the vessel wall, thereby affecting the stresses that eventually impinge on the interior surface. In any event, it is apparent that deep textures can lead to a reduction of interior tensile stresses and thereby improve thermal shock resistance.

A second set of questions, regarding spalling, led to several Stage 2 tests (Table 4). In Stage 1, shallow texturing decreased by more than half the number of thermal spalls compared to smooth exteriors. The obvious question is: Could coarser textures reduce or eliminate spalling entirely? The answer turned out to be a rather definitive yes. Vessels having smooth interiors and a deep texture (26) or stucco exterior (27) did not spall. Clearly, deep textures can markedly reduce thermal spalling.

There is no mystery about how deep textures diminish spalling. In order for spalling to occur, steam must form in the vessel wall; unless that steam can rapidly reach and penetrate the exterior surface, it will concentrate tensile stresses on weak areas of the paste, causing local failures and thus spalling. By providing a much greater surface area, deep textures increase the permeability of the exterior surface, allowing steam to escape at a higher rate. This slows down—or even stops—the production of spalls.

A second question regarding thermal spalls involves interior treatments. It was learned in Stage 1 that spalling is greatly affected by the extremes of interior permeability. Our question is: How do interior treatments having permeabilities intermediate between PAM-coating and smoothing influence thermal spalling?

Four vessels with polished interiors permitted comparisons with smooth-interior vessels from Stage 1; two had shallow-texture exteriors (22, 25), while the other two were smooth (36, 37). In both cases, the polished interiors, with their lower permeability, slightly reduce the number of spalls (a mean of 44 to 36.5 spalls for smooth exteriors; a mean of 10 to 3 spalls for shallow-texture exteriors).

Interior smudging did not produce definitive results. The first vessel (20), smudged interior and smooth exterior, had nine spalls—many fewer than its unsmudged equivalents. However, a second vessel (21), smudged interior and shallow-textured exterior, had 18 spalls. Given the textured

exterior, we would have expected much less spalling. Though the number of spalls is within the range of a vessel with a shallow-textured exterior and smooth interior (compare to vessel 9), the pot performs as if the interior smudging had no effect on the spalling.

There are several possible explanations for these untidy results. The most obvious is low sample size, which we cannot rule out. A second hypothesis, also not easily dismissed, blames minor variation in vessels, especially basal thickness. A third explanation is that the smudging process reduces the effective firing temperature, making a weaker pot that is more susceptible to spalling. Indeed, firing temperature has a dramatic effect on spalling. Two pots, one fired to 600°C (14) and the other to 800°C (13), were produced with smooth interior and exterior surfaces. The low-fired vessel had 56 spalls, while the high-fired vessel had only one. Clearly, if smudging decreases the effective firing temperature by accelerating the cool-down process, spalling could increase. Because of the 15-minute soak, however, we doubt that differences in effective firing temperature would be sufficient to produce the excess spalls. A fourth hypothesis is that the imperfect smudging process also slightly reduced the permeability of the *exterior* surface, which could create a greater-than-expected number of spalls. This latter possibility seems especially likely in view of the highly variable smudges from pot to pot. In a previous experiment the permeability of smudged interior surfaces varied by a factor of 2 (Schiffer 1990a:Table 1, vessels 46–53). Although permeability was not measured in the present experiment, we believe the smudged surfaces also vary considerably.

A final vessel, smudged interior and exterior, deepens the mystery. This vessel (38) had only 8 spalls. The interior was extremely well smudged, however, which may have greatly reduced the vessel's permeability. In addition, by depositing pyrolized organic matter in pores of the vessel's exterior, smudging may have caused an increase in strength (and thus resistance to spalling). In any event, it is apparent that smudging can sometimes reduce spalling. The most definitive finding from tests of the smudged vessels, however, is that we need to improve our technique.

## SUMMARY OF RESULTS

Interior and exterior surface treatments profoundly influence the resistance of clay cooking pots to thermal spalling and to thermal shock cracking.

By affecting the flow of water into the vessel wall, interior treatments affect a vessel's susceptibility to spalling. The more permeable surfaces (e.g., smooth, smudged, and polish) allow the vessel wall eventually to become water saturated, whereas the least permeable surfaces (e.g., PAM, Kalinga resin) prevent water absorption. Vessels with largely impermeable interior surfaces (and thus dry walls) do not suffer thermal spalls. On the other hand, vessels with saturated walls are very vulnerable to spalling, depending on the permeability of the exterior surface. Saturated vessels with low- and moderate-permeability exteriors (smudged, polish, smooth, and even shallow texture) can spall, sometimes badly, whereas those with highly permeable exteriors (e.g., deep texture, stucco) are protected.

Surface treatments, interior and exterior, also affect the occurrence of thermal cracking, which begins on the interior basal surface of susceptible vessels. Pots with permeable interior surfaces, and thus water-saturated walls, do not crack because the mean temperature (across the thickness of the wall) is lower, giving a smaller thermal gradient at the surface, and so a smaller tensile stress than the coated, impermeable vessels. Vessels with interior treatment of low permeability, such as PAM, are thus more likely to suffer thermal cracking than an uncoated vessel. Other such treatments that form coatings (e.g., Kalinga resin, polyurethane varnish) increase the tensile strength of the vessel's interior surface, countering the high tensile stresses resulting from thermal gradients. The performance of vessels whose interior surfaces make them crack prone can be improved by deeply texturing the exterior surface (e.g., corrugation or stucco), but the mechanism for this process is unclear.

The above relations are strongly mediated by other technical choices. For example, higher firing temperatures reduce thermal spalling, but at the expense of more thermal cracking. Similarly, thermal cracks are more likely to afflict larger vessels.

EXPLAINING TECHNOLOGICAL VARIABILITY AND CHANGE

Experimental archaeology yields correlates—principles of human–artifact interactions (Schiffer 1975, 1976:12–14)—that can be incorporated into explanations of technological variability and change (Schiffer 1992; Schiffer and Skibo 1987). As a result of the present study, we now know that certain surface treatments, by mediating permeability and heat propagation, can have a behaviorally significant influence on a ceramic vessel's resistance to thermal shock cracking and thermal spalling. How can these new principles be applied to cases from prehistory?

In traditional practice, the findings of an archaeological experiment would be immediately exploited by the investigator to help solve the prehistoric puzzle that gave rise to the experiment in the first place. The danger in this practice is that a single experiment, even if done well, cannot reveal the complex causal relations in which a particular finding needs to be embedded. An experimental archaeology, on the other hand, is driven by the desire to understand, often independently of any specific prehistoric problem, the entire set of causal relations that can affect variability in some aspect of technology. In the long run, we maintain, the families of related correlates that experimental archaeology produces will generate a new level of understanding that can illuminate many archaeological cases.

Let us take an example from the American Southwest to highlight how the results of experimental archaeology could help the investigator to frame inquiry capable of furnishing, eventually, sound explanations.

As is well known, Anasazi and Mogollon potters adopted a technique of vessel manufacture known as corrugation, which results in a deeply textured exterior surface. Found on "cooking" pots and on some "storage" vessels, corrugation has long intrigued southwestern archaeologists. Why was this technique, possibly more labor intensive and demanding a high level of skill, employed for the most mundane ceramics? The obvious explanation has been that corrugation reflected "cultural" factors or style, and was unrelated to the vessels' techno-function. Also mentioned is the possibility that deep textures like corrugation might enhance heating effectiveness (e.g., Herron 1986; McGregor 1965:282; Rice 1987:232), but recent experiments—some in our lab—have demonstrated otherwise (Schiffer 1990a; Young and Stone 1990). Deep texturing does not improve and can, depending on interior surface treatments, seriously degrade heating effectiveness (Schiffer 1990a).

The experiments reported above indicate that a deep texture can increase thermal shock resistance and reduce thermal spalling on cooking pots. Are these performance characteristics, finally, the reason why Anasazi and Mogollon potters turned to corrugation? If only it were that simple! If nothing else, nearly a decade of experimental archaeology has taught us that individual relationships between technical choices and performance characteristics are an insufficient basis for generating explanations for particular archaeological phenomena. We also need a causal framework sufficiently encompassing to allow specific technological features to be adequately contextualized.

Although that framework is still in its infancy, our accumulated experimental findings and theoretical considerations indicate that any one technical choice (for example, to corrugate) affects many use-related performance characteristics—some positively, others negatively (Schiffer 1992; Schiffer and Skibo 1987). Corrugation, for example, not only enhances thermal shock and spalling resistance, while sometimes impairing heating effectiveness, but it can also impact evaporative cooling effectiveness in certain use contexts (Schiffer 1988). In addition, "thought experiments" allow us to hypothesize that a deep texture might improve the "graspability" of hot or wet pots (cf. Wahlman 1972:319), while making it more difficult to clean the exterior surface. A deep texture may also affect a vessel's impact resistance, but this remains to be shown. Needless to say, a great many use-related performance characteristics might be influenced by a deep exterior texture.

Additional thought experiments allow us to hypothesize that manufacture-related performance characteristics could also be affected by a technical choice like corrugation. For example, by conferring a greater surface area on vessels, a deep texture may promote more rapid and even paste drying as well as more fuel-efficient firing. Such possible effects, which could enhance a potter's ability to make large vessels, would come at the expense of the greater skill needed to master the technique and, perhaps, added effort required to make pots. Clearly, new experiments are needed to evaluate these hypothesized effects.

Not only are use- and manufacture-related performance characteristics altered by any given technical choice, but each of those performance characteristics in turn responds to additional technical choices. For example, as noted above, thermal shock resistance is affected by exterior surface treatments as well as by firing temperature, paste characteristics, wall thickness, vessel shape and size, and interior surface treatment, among others. Similarly, paste drying rates also vary in response to clay and temper characteristics.

Technical choices can also influence performance characteristics that facilitate a vessel's socio- and ideo-functions. Corrugation, for example, allows some surface features to be seen on a soot-blackened pot or felt in a darkened storage room. Variations in corrugation might also permit the identification of individual potters. Such possible effects are not confined to use contexts. During manufacture, for example, mastering the subtleties of a difficult technique, such as corrugation, may allow potters in a work group to compete for prestige among their peers.

An appreciation for the richness of the relations between technical choices and performance characteristics should suffice to rein in one's enthusiasm for applying limited experimental findings to a specific case. But it is still more complex. As we have argued elsewhere (Schiffer 1992; Schiffer and Skibo 1987), certain (derivative) technical choices may result from the effort to undo deleterious effects of other (fundamental) technical choices. For example, could corrugation have ameliorated the greater thermal stresses that afflicted larger cooking vessels? Or was corrugation a way to strengthen pots weakened by low firing temperature and a coarse paste? Moreover, a given technical choice may have rather different functions at different times in a technology's history. When corrugation first appears, it is as neck banding on some Anasazi vessels; only later does it cover the entire body. Perhaps in its initial incarnation corrugation had a socio- or ideo-function, or enhanced "graspability"; eventually it may have come to serve several symbolic and utilitarian functions.

Ironically, a better understanding of the causal relations between technical choices and performance characteristics, furnished in part by our program of experimental archaeology, has not yielded an immediate explanation of why prehistoric artisans in the American Southwest corrugated their pots. It can, however, suggest the need for new experiments (e.g., does corrugation affect impact resistance and paste drying rate?). More importantly, perhaps, it brings us to the realization that crucial information about the behavioral contexts of corrugated vessels is still lacking. How were corrugated pots in different size and shape classes actually used? Did those uses vary over time or space? At what temperatures were the pots fired? How did the clays exploited by Anasazi and Mogollon potters affect thermal shock resistance? Such questions need to be addressed with ceramic use-alteration analyses (e.g., Hally 1983, 1986; Schiffer 1989; Skibo 1992), laboratory measurements on prehistoric specimens (e.g., Rice 1987), and experiments with local materials (Bronitsky 1986; Skibo 1992:18–28). It would appear that the explanation of technological variability and change is a challenging and information-intensive enterprise (for examples, see Schiffer 1991, 1994).

Experiments in archaeology, we suspect, reinforce a view of explanation, derived from poorly developed correlate theory and promoted by the immediate needs of the prehistorian, that is much too simplistic. We suggest that a long-term program of experimental archaeology, in contrast, calls attention to the actual complexity of causal relations and to the kinds of case-specific information that can lay a foundation for better, deeply contextualized explanations of technological variability and change.

## CONCLUSION

Though enjoying a long history in archaeology, experimentation is often still practiced on a weekend basis. We have argued that the sophisticated questions now being asked about ancient technologies demand greater development of an experimental archaeology. The arguments have been illustrated with a case study concerning the effects of surface treatment on the thermal response of clay cooking pots. To underscore the relation between the experiment reported here and the technological tradition of which it is a part, we described the experiments in detail and attempted to account for our own technical choices. The new experiments revealed that interior and exterior surface treatments can influence a cooking pot's susceptibility to thermal shock cracking and thermal spalling. Finally, we argued that an experimental archaeology can contribute to the creation of more

satisfying, more richly contextualized explanations of technological variability and change. Such explanations require the principles produced by experimental archaeology, higher-level correlate theory, and a host of context-specific information.

## APPENDIX

A simple physical model of the experiments carried out can help to explain when and where thermal cracking takes place. The model, which deals with heat transport, is based on a fundamental equation relating heat, thermal conductivity, and temperature change across a distance. For a flat slab (i.e., a cross section of a vessel wall), the equation simplifies to:

$$Qdx = -kdT, \quad \text{or relatedly,}$$

$$Q = -k(dT/dx)$$

where      $Q$ is the heat exhanged normal to a unit area
              k is the thermal conductivity
              $dT$ is the change in the temperature $T$
              $dx$ is the change in the distance $x$.

The equation essentially allows for balance in heat transfer, and states that for a body of constant thermal conductivity (k), the temperature gradient is linearly related to the heat flow across the distance $x$.

Further, we know that thermal stress is directly related to changes in temperature. Thus, if we can map the temperature gradient through the course of the experiment, we can understand the sources of tensile and compressive stresses in the vessel wall. It is intuitive that if the surface temperature is greater than the mean temperature through the vessel wall, then the surface, expanding because it is hot, is held back by the bulk of the vessel, and experiences a compressive stress. On the other hand, if the surface temperature is less than the mean wall temperature, the surface is "pushed out" by a core that is still "thermally expanded," and so experiences a tensile stress. This is summarized as:

$$T_{\text{surface}} < T_{\text{mean}}, \quad \text{tensile stress}$$

$$T_{\text{surface}} > T_{\text{mean}}, \quad \text{compressive stress.}$$

With this information in hand, it is possible to model the experiments carried out in this study. Important information includes: (1) profiles of thermal gradients through the vessel wall $(dT/dx)$, (2) mean temperatures through the vessel wall, and (3) profiles of stress distribution across the vessel wall.

Four stages in the experiment are considered as critical points to model: (1) the initiation of the experiment $(t_0)$, when the flame has just been turned on, (2) after some time, when equilibrium (or the steady state [s.s.]) has been reached (here 5 minutes, or $t_{s.s.}$), (3) after the flame has been turned off $(t_1$, greater than 5 minutes), and (4) after the water has been drained from the vessel, 2 minutes after Stage 3 $(t_2)$. Two types of vessels were used in this experiment: coated and uncoated.

At $t_0$, the exterior surface is subjected to a high temperature, while the mean temperature through the vessel wall remains near room temperature. At 5 minutes $(t_{s.s.})$, the system has achieved steady state, which for a vessel of constant thermal conductivity means that there is a constant increase
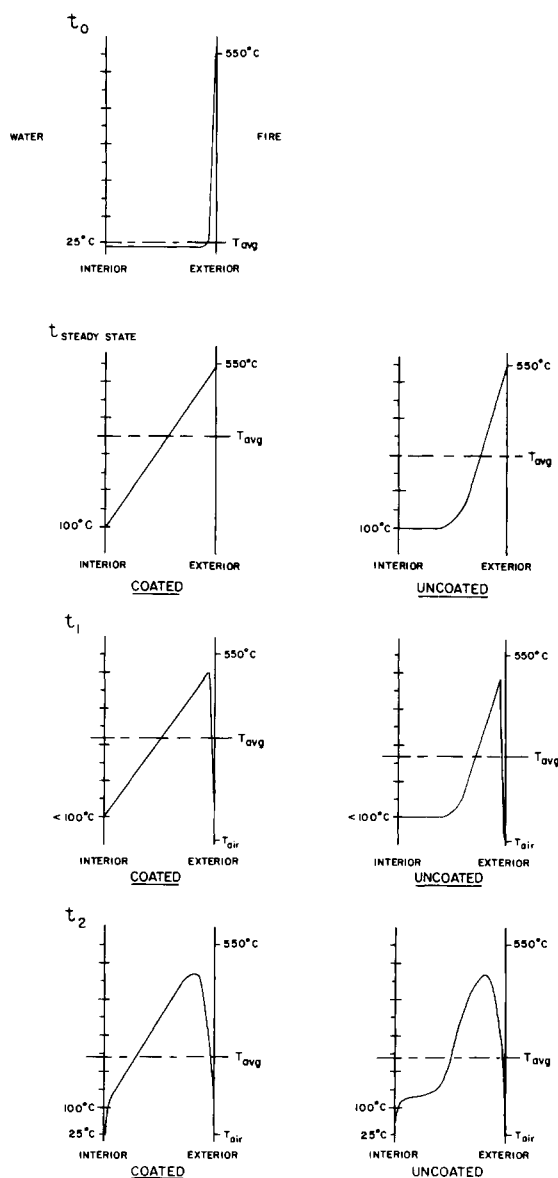
**Figure 2.** Temperature profiles through the wall of a pot during four stages of the experiment: $t_0$ (heat turned on), $t_{s.s.}$ (after 5 minutes), $t_1$ (just after turning off heat), and $t_2$ (2 minutes later, after draining water).

in temperature from the cool side of the vessel (interior) to the hot side of the vessel (exterior). For a coated vessel, the interior temperature is pinned *at the surface*; for an uncoated, permeable vessel, the water penetrates the wall, maintaining a temperature near 100°C *into the wall* for some distance. The result is that the mean temperature through the entire vessel wall is lower in the uncoated vessel than in the coated vessel. When the flame is turned off at $t_1$, the exterior surface is subjected to an ambient temperature near 25°C. (The temperature of the exterior surface will be higher than 25°C owing to radiation of heat from that surface; the effects of radiated heat are not explicitly treated in this model.) The mean temperature of the vessel wall is lower than the temperature of the fire, which is at 550°C, and the water is below 100°C. This is illustrated in Figure 2. Finally, after 2 more
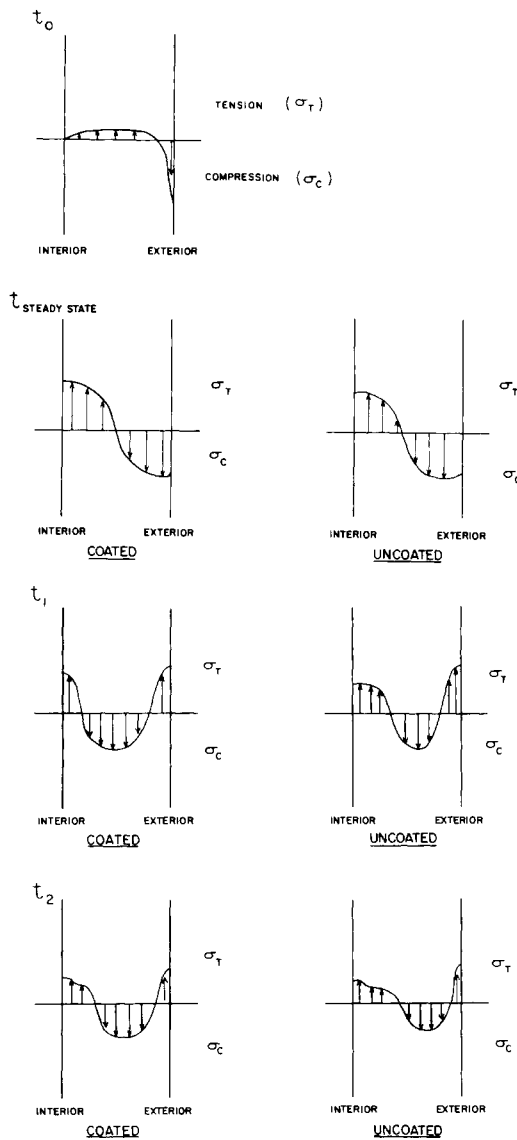
**Figure 3.  Stress profiles through the wall of a pot during four stages of the experiment: $t_0$ (heat turned on), $t_{s.s.}$ (after 5 minutes), $t_1$ (just after turning off heat), and $t_2$ (2 minutes later, after draining water).**

minutes ($t_2$), when the water is drained from the vessel, the interior surface is subjected to ambient temperatures near 25°C. The mean temperature of the vessel is once again lower than at time $t_1$.

These temperature profiles are then directly translated into stress profiles by comparing the surface temperatures to the average temperatures through the wall. These results are shown in Figure 3. A comparison of the relative tensile stresses experienced at the interior of the vessel during thermal cycling shows that the largest tensile stresses are developed at steady state for the coated samples. This results from the large difference in temperature between the interior surface and the mean temperature through the vessel wall.

On the other hand, the expectation that the exterior surface would crack or spall during cooling based on large tensile stresses (Figure 3) is not supported by the experimental evidence. In fact,

spalling occurs during the heating cycle. In this case, the heat-transfer model provides us with contradictory information. As a result, we can see that the expansion and pressure of steam in the vessel wall must dominate the heat-transfer-induced compression at the exterior surface during heating. It is possible that because spalling generally increases as the number of cycles increases, the high tensile forces on the exterior surface experienced during cooling aid in degrading strength through microcracking. Again, however, it appears that the steam is the primary force in spalling.

Thus, by carefully modeling the thermal behavior of the vessel through the various stages of the experiment, one can make a good case for cause and effect, as in the thermal cracking on the interior surface of PAM-coated vessels. When the model does not agree with experimental evidence, however, it suggests that other forces are dominant, and need to be considered, just as is seen with the spalling phenomenon.

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